

Design of an Abort Gap Monitor for the Large Hadron Collider[†]

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Abstract. We present a study of an abort gap monitor for the Large Hadron Collider. This is a critical instrument in the machine protection chain and high-accuracy specifications have been laid out for it. We briefly discuss the different options for designing the monitor and present experimental results obtained using what we believe is the most suitable technique, based on a photomultiplier with a gated microchannel plate.

INTRODUCTION

The Large Hadron Collider rings are characterized by an enormous amount of stored energy (350 MJ/beam), so that special care has to be taken in avoiding accidental beam losses [1]. A beam dumping system, capable of handling such high energies, has been designed, with its fast kickers placed near IR6 for steering the beam into the high-power dump block. A 3.3 μ s long gap along the machine, corresponding to the abort kickers' rise time, has to be kept free of charges. This is generally referred to as the *abort gap*. Any particle present in the abort gap at the time of the kickers' firing would not receive the proper kick and would therefore hit machine components.

The maximum tolerable proton densities in the gap, under the level expected to cause quenches in the superconducting magnets, are reported in [2] for injection and nominal

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energies. The thresholds at intermediate energies can be obtained by interpolation and are anyway less important since the machine operates at those energies for the limited amount of time during the ramping.

Various considerations suggest subdividing the abort gap length into 100 ns long intervals, so that the threshold charge densities are $6 \cdot 10^6$ p/100 ns and $4 \cdot 10^9$ p/100 ns at 7 TeV and 450 GeV respectively.

There are different mechanisms leading to accumulation of charges in the abort gap. Injection timing errors produce an instantaneous accumulation of charges above the maximum threshold, even in the case of the pilot bunch used for pre-injection testing. In this scenario, it is sufficient to detect this circumstance before the following injection batch, which takes place some 20 s later.

Diffusion processes and capture of unbunched beam can also cause the abort gap to become populated and the time scales associated to these phenomena go from around 1 s to tens of seconds [3]. Based on these considerations, the maximum integration time for monitoring the abort gap has been set to 100 ms.

TECHNOLOGIES FOR MONITORING THE ABORT GAP

There are a number of methods that one can use in principle for detecting the presence of charges in the LHC abort gap. We can group them in two categories, depending on whether they detect the wake-field associated to such charges, or measure the emitted synchrotron radiation. Whichever the chosen method might be, it is required to have a fast response time, to be able to monitor the first empty RF buckets in the gap, following the bunch train. These buckets are the first to fill due to intrabunch diffusion and are the most difficult to monitor being next to high-current bunches.

Wake-field based methods

Beam current monitors (BCM), fast current transformers (FCT) and beam position monitors (BPM) could, in principle, be used for monitoring the abort gap. All these devices can be designed with a bandwidth large enough to be able to discriminate single bunches. They also have the intrinsic advantage to be already included in the LHC

design, for other uses, so that there is no need to build and install a separate component, though this would certainly be advisable as the Abort Gap Monitor is to be part of the machine protection system.

The main disadvantage with using the devices mentioned above is that they do not have the necessary high signal-to-noise ratio, when the bandwidth is of the order of 1 GHz or higher. The threshold charge at 7 TeV has a peak current of less than 10 μA and we have to be able to discriminate from the last filled bunch which has a peak current 10^6 times higher.

It is possible to rapidly gain switch a FCT to prevent saturation from the bunch train, but this has been realized only at slower speeds than those we would require [4, 5].

Synchrotron light based methods

The presence of particles in the abort gap can also be detected by observing the synchrotron light they emit. In the LHC there is a synchrotron light port, designed for a transverse profile monitor. A possible mirror configuration for longitudinal measurements, that doesn't interfere with the transverse diagnostics and that could be used for monitoring the abort gap, has been studied in [6]. There are a variety of instruments that can be used to measure the synchrotron light; again, like in the wake-field case, we need the necessary time response properties and sensitivity. In addition the number of photons available depends on the particular machine energy. We focus on the injection and nominal energies of 450 GeV and 7 TeV respectively, as the machine will be operating at those two energies for most of the time. Performance at intermediate energies during the ramp can be derived by interpolation.

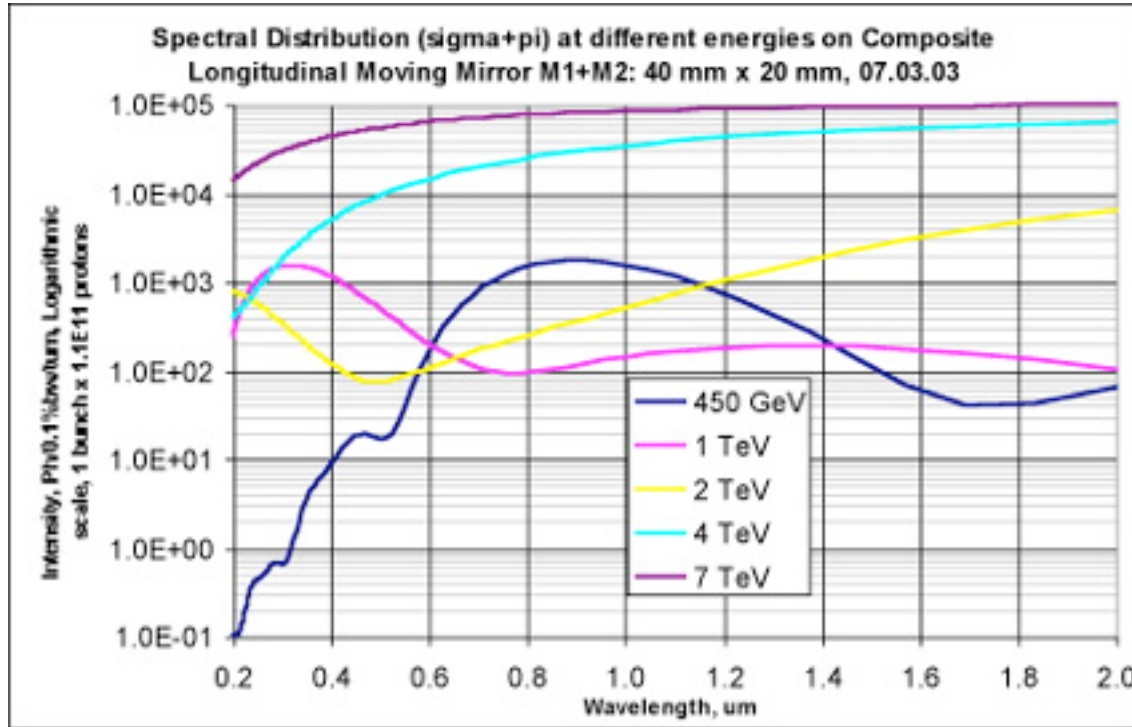


Fig.1 Photon flux from nominal bunches at the synchrotron light diagnostic port. (M. Facchini)

Figure 1 shows the calculated photon fluxes at various energies. There is a number of devices one can use to detect this synchrotron radiation: streak camera, photomultipliers (PMT), avalanche photodiodes (APD). All these devices are commonly used for measuring the beam's longitudinal distribution and have the time resolution and sensitivity necessary for the application under investigation here.

The streak camera main disadvantage is in the long time lag between data samples; typical repetition rates are of the order of 1 Hz. A single sample can cover the entire abort gap, but the repetition rate is below specifications.

APD's have very good quantum efficiency, but their typical dark current levels are 50 to 100 times higher than in PMT's. The main problem with using APD's for gap monitoring is their relatively slow gating speed and recovery time, which would effectively create a blind spot in the first part of the abort gap. This part is actually the most likely to become filled by charges diffusing from the last bunches of the train, so that we identified in a

gateable microchannel-plate PMT (MCP-PMT) the device of choice for abort gap monitoring.

MONITORING THE LHC ABORT GAP WITH AN MCP-PMT

Commercially available MCP-PMTs [7] are the ideal instrument for such a task due to their high gain, fast gate, low noise and variety of peak wavelength of their spectral response. Also the low voltage required for gating and their reduced dimensions (Fig.2) are other beneficial features that make the use of such a device particularly simple.

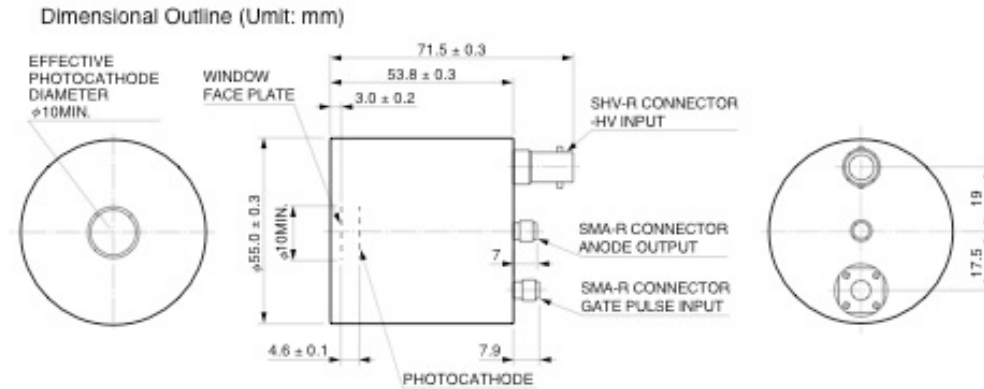


Figure 2. Hamamatsu gateable microchannel-plate photomultiplier R5916U-50 Series.

The minimum gate width for our Hamamatsu R5916U-50 MCP-PMT is 5 ns, with a gate rise time of 1 ns. These numbers are entirely suitable for use in the LHC, where the sampling window is 100 ns and the distance between RF bucket is 2.5 ns, so that it is possible to gate out filled buckets nearby the abort gap.

Time resolution for the measurement is dominated by the device's transit time spread (which can be estimated as equal to the instrument response function). Figure 3 shows that for our device that is roughly equal to 100 ps, again well below our resolution requirements. The response decreases by 3 orders of magnitude in 1 ns, which is substantially shorter than the 2.5 ns bucket separation in the LHC.

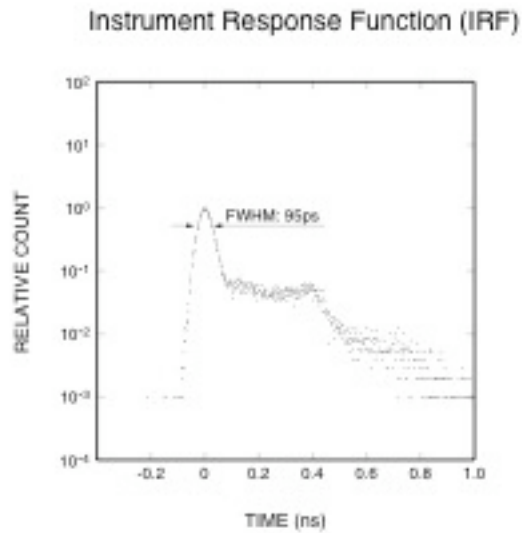


Figure 3. Instrument Response Function for the R5916U-50 MCP-PMT.

The main parameters for the Hamamatsu tube are summarized in Tab.1. Given the device maximum duty factor of 1%, different strategies are possible for mapping the abort gap. The most immediate one is using a 100 ns gate width, which allows for taking one measurement every turn.

Gate rise time:	1 ns
Gate length:	5 ns ÷ 10 μ s
Max duty cycle:	1%
Gate voltage:	10 V
Max. gain:	10^6
Output rise time:	180 ps
Transit time spread:	90 ps
Dark counts:	10 cps

Table 1. MCP-PMT specifications (Hamamatsu R5916U-50)

To cover the entire abort gap 33 such measurements are necessary, with the timing of the gate continuously shifted to move the observation window along the gap. Furthermore, the 100 ms allowable integration time, as per specification [2], permits to accumulate and average 34 measurements of each individual sample. From Fig.1 we can calculate the

number of photons emitted by a 100 ns portion of the abort gap, containing the average maximum allowable proton density, and collected on the longitudinal mirror in a single pass. After simple calculations, we find that the number goes from ~ 200 at 7 TeV to ~ 70 at 450 GeV in a 10% bandwidth centered at 500 nm.

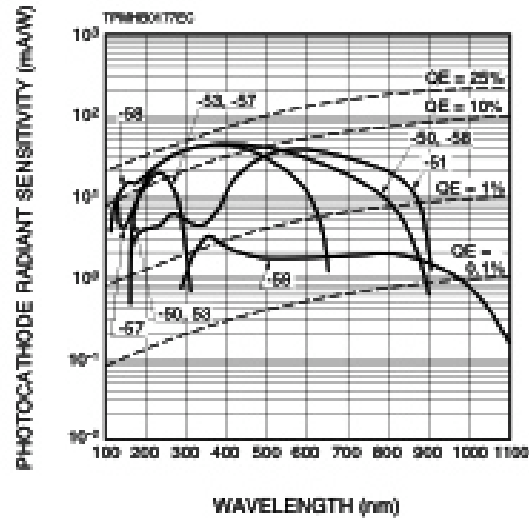


Figure 4. Sensitivity and constant quantum efficiency curves for different MCP-PMT models.

Figure 4 shows the spectral response for different models of the Hamamatsu tube available. Combining this information with the expected photon flux in Fig.1, we can identify the spectral region around 500 nm as the most suitable for our application. Let's conservatively assume a 5% quantum efficiency over a 10% bandwidth at 500 nm. This yields a 100 ms integrated photon count in the $1 \div 3 \cdot 10^3$ range, depending on the machine energy. This number can still be increased at the price of a marginally higher complexity in the MCP-PMT signal treatment. An 890 ns gate is the longest still allowing to take one measurement per turn. The information on individual 100 ns samples has to be extracted from this longer measurement, but we have seen that the tube has a far better resolution than required. With this gate width, the light from each 100 ns portion of the abort gap is sampled around 300 times in an integration time, thus increasing the accumulated photon counts by almost a factor of 10.

EXPERIMENTAL RESULTS AT THE ALS AND TEVATRON

We conducted a series of experiments both at the Advanced Light Source and at the Tevatron, using our Hamamatsu tube to detect synchrotron radiation. The results obtained so far prove how much a MCP-PMT based abort gap monitor would be suitable for application to the LHC.

	<i>LHC</i>	<i>ALS</i>	<i>TEVATRON</i>
Revolution time (T_{rev})	88.9 μs	657 ns	21 μs
Bunch length (σ_t)	620 ps	30 ps	1600 ps
Gap length (G_t)	3.39 μs	120 ns	3 x 2.4 μs
Bunch charge (q_b)	18 nC	0.9÷6.5 nC	53 nC
RF buckets spacing	2.5 ns	2 ns	19 ns

Table 2. Beam parameters for LHC, ALS and Tevatron

ALS experiments

Several parameters of the ALS storage ring (Tab.2) make it a good place for testing a possible utilization of a MCP-PMT as an abort gap monitor for the LHC: similar distance between RF buckets and a gap length equal to the length of an LHC sample. The ALS ring also features a special high current bunch (referred to as *camshaft*) in the middle of its fill gap which is followed by very low current parasitic bunches, due to diffusion of electrons from the camshaft into the following RF buckets. This is particularly interesting from the point of view of studying eventual saturation phenomena in the MCP-PMT, which could interfere with the detection of a low charge density next to a much larger one.

Our experimental station is at the ALS diagnostic beamline (BL 3.1) which uses the synchrotron radiation generated in a bending dipole (1.3 T).

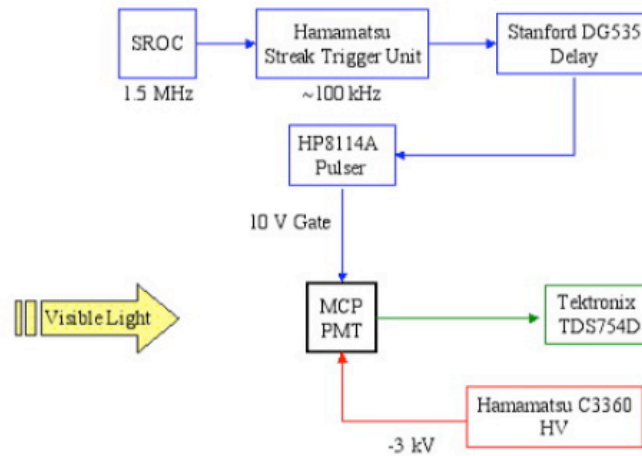


Figure 5. Block diagram of the experimental setup at the ALS.

Figure 5 shows the block diagram of our experimental setup at BL 3.1. The 10 V gating pulse, synchronized to the ring orbit clock (SROC), can be shifted around using a delay box and the internal pulser capabilities.

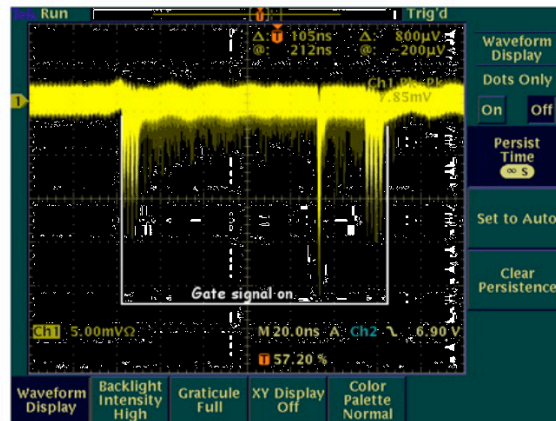


Figure 6. The 104 ns long ALS fill gap with camshaft.

Figure 6 shows an image of the entire ALS fill gap. Four regularly filled bunches can be seen at the beginning and at the end of the gap and the camshaft is the larger signal between them. This picture was obtained setting the oscilloscope on an infinite persistence time, so that we are indeed observing data accumulated over a very large number of turns.

Figure 7 gives an idea of the instrument time resolution. This image was taken with no averaging and individual bunches are easily resolved.

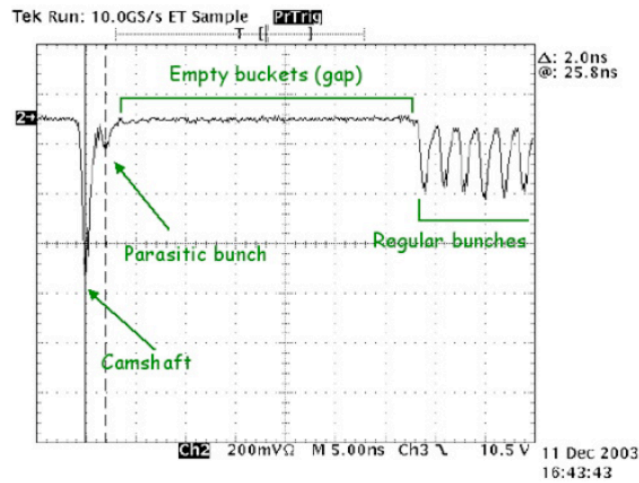


Figure 7. Image of the camshaft, trailing parasitic bunch and first 6 bunches of the ALS fill train. Averaging is off.

In Fig.8 we show how it is possible to detect very low intensity bunches simply by gating out nearby large signals. The two parasitic bunches after the first one (which is also visible in Fig.8a) shown in Fig.8b have an estimated population of roughly 1% of a regular bunch, showing that photocatode saturation is not an issue.

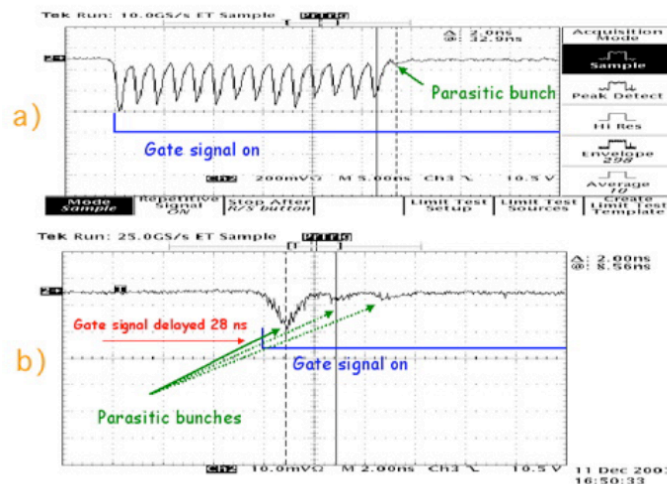


Figure 8. a) Beginning of the ALS gap and nearby 14 bunches. b) Filled RF buckets are gated out by shifting the gate signal

Furthermore, a comparison of signal base levels with gate on and off shows the very low noise characteristics of the instrument and the absence of dark counts.

Tevatron experiments

We also conducted tests at the Tevatron. In this case we wanted to use the MCP-PMT in photon-counting mode to verify its performance with a reduced photon flux. We also wanted to measure synchrotron radiation emitted by unbunched beam (which can possibly be present in proton rings) and check how hard it is to separate that signal from the measurement background. Our experimental setup was similar to the one used at the ALS (Fig.5), with minor differences to allow operating in single-photon counting mode and with a noise subtracting mechanism.

The measurement of the final quarter of one of the three abort gaps is shown in Fig.9. The first bunch of the train, following the gap appears as a series of out-of-scale signal in the rightmost part of the figure, as it is typical of this kind of measurement. The centre of the RF buckets are marked by red crosses and the measurement shows how diffused protons bunch-up. The front half of the abort gap, which is kept clean by the injection process, would be more interesting from the point of view of observing unbunched beam. We couldn't perform those measurements yet, due to problems in the machine. We are planning to take new measurements in the immediate future.

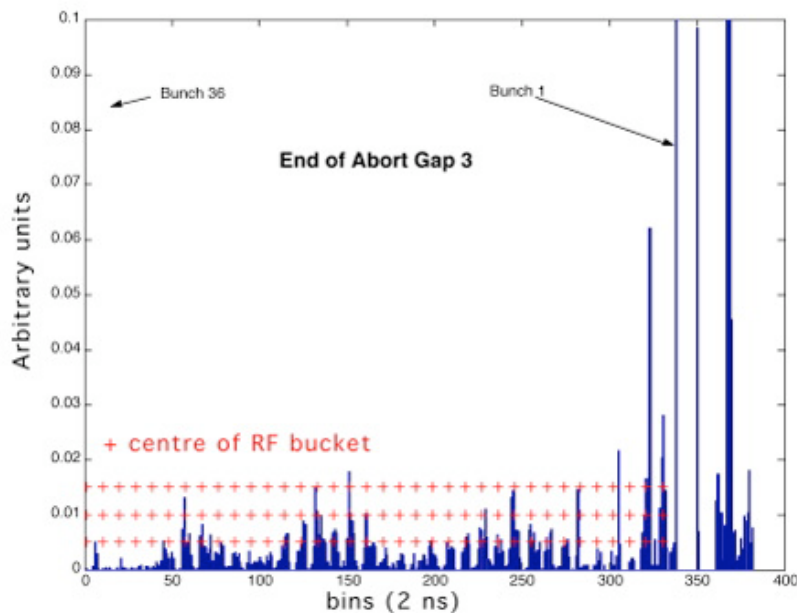


Figure 9. 800 ns sample of the Tevatron abort gap and first filled bucket.

Bench measurements

We also performed bench measurements to test the instrument's response at the photon fluxes expected in the LHC. We used an optical power meter, bandpass filters and diaphragms to obtain a light intensity equal to what calculated for the LHC in the bandwidth we want to operate our abort gap monitor (Fig.10). The MCP-PMT gate is enabled for 100 ns, which is likely the gate length to be used in the LHC and the gate signal repetition rate is also chosen accordingly to what would be used in practice.

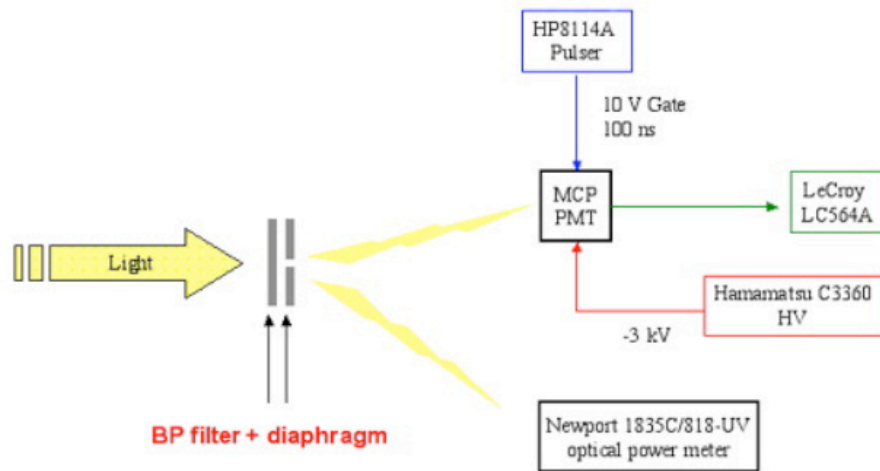


Figure 10. Experimental setup for sensitivity measurements.

Figures 11 and 12 show the results for a number of photons corresponding to the number emitted in 100 ns by a uniform charge distribution with total charge equal to the threshold value for the abort gap monitor.

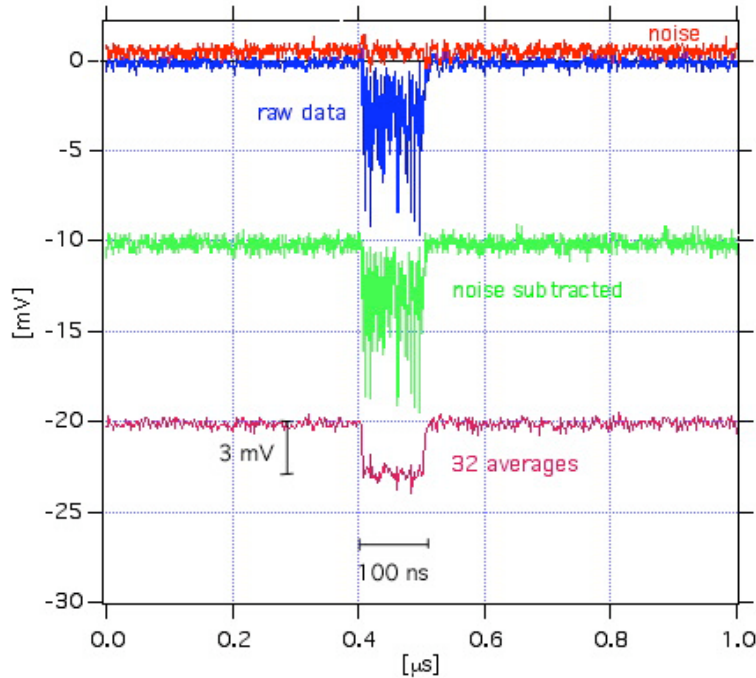


Figure 11. MCP-PMT output for 180 photons/sample at 488 nm (1 nm bandwidth).

Figure 11 was taken using a narrow filter (0.2% bandwidth) centered at 488 nm wavelength, where our MCP-PMT has maximum quantum efficiency. The light intensity measured was adjusted so as to be equivalent to a ~ 180 photons/100 ns flux, which is roughly the flux expected to be generated by the abort gap threshold charge at 7 TeV. The noise correction essentially is used only to get rid of some residual reflected signal due to mismatch in the experimental arrangement, as the MCP-PMT noise is negligible. In any case, the raw signal can be easily detected, even from a single pulse. The 32 averages that can be used in the final abort gap monitor generate a rather clean 3 mV output pulse. For this experiment we also run off the MCP-PMT maximum gain, since its output was easily detectable.

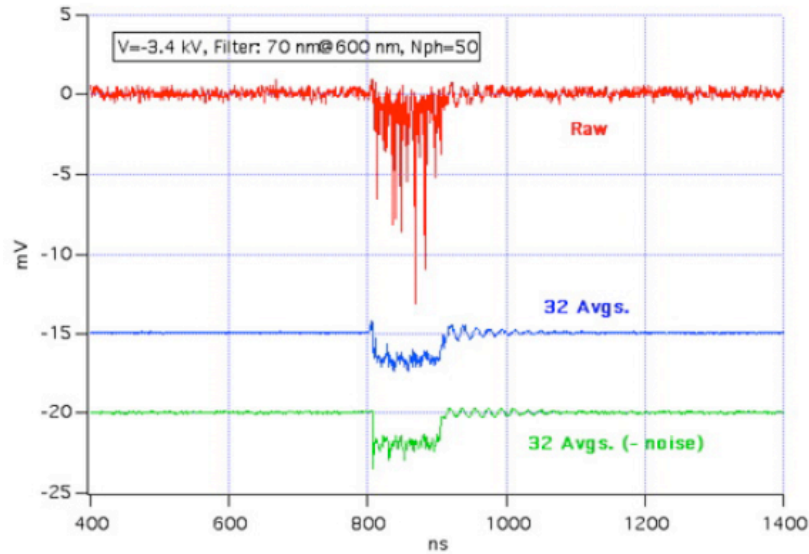


Figure 12. MCP-PMT output for 50 photons/sample at 600 nm (70 nm bandwidth).

In Fig.12 we show a similar measurement for the photon flux expected at 450 GeV. We used a different filter, to test the device on a larger bandwidth, and had to raise the gain to its maximum. As in the earlier case, the output generate is of the order of a few millivolts and its detection doesn't present any particular problem.

We also measured the intensity of the synchrotron light available at the ALS and estimated that the number of photons generated by a single ALS standard bunch is roughly 40÷50 times the threshold at 7 TeV. Consequently the measurements of the parasitic bunches shown in Figs.7 and 8 is a good exemplification of what would be required in the LHC.

DATA ACQUISITION

The data acquisition from the MCP-PMT doesn't present particular difficulties. As previously mentioned, it is sufficient to use a 100 ns long gate on the MCP-PMT; the 100 ms integration time allows to accumulate 33 such measures of the same 100 ns long portion of the abort gap; the output level is continuously compared to a predetermined threshold level and, if necessary, an alarm is generated. Then the gate is shifted by 100 ns and the process is repeated until the entire abort gap has been mapped.

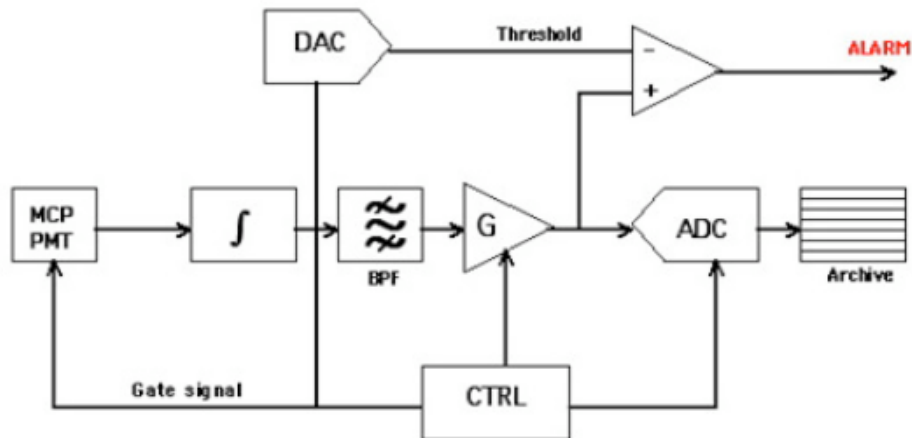


Figure 13. Scheme of the signal acquisition and processing for the abort gap monitor.

A possible block diagram for the process just described is shown in Fig.13. The gain is changed according to the ring energy and the instrument's output can be archived in digital form. In fact, since a charge distribution above threshold can fall across two contiguous 100 ns sample, without triggering an alarm in neither, the gate signal would be shifted by 50 ns, rather than 100, so that each sample would overlap with the contiguous ones. This reduces the maximum number of averages per sample to 16, but we have seen that the signal levels in the LHC are adequate, anyway.

In case the number of photon should prove to be much lower than what estimated it is still possible to improve the signal-to-noise ratio using a slightly more complicated acquisition scheme. The gate length can be increased to 825 ns, the longest value that still allows taking one measurement per turn, compatibly with the 1% maximum duty cycle. This way, it takes only four samples to map the entire abort gap and each sample can be averaged almost 300 times in 100 ms. Each 825ns long sample needs to be resampled at 100 ns to achieve the required resolution, but this can be easily achieved using a series of integrators triggered in succession. The 89 μ s between samples are an ample interval for such a task. Each integrator's output is digitized and accumulated from sample to sample in a memory register. These registers are continuously polled and compared to the threshold level.

A calibration for the abort gap monitor can easily be performed at operations start by circulating a single bunch with the required charge and recording the MCP-PMT output at various energies.

CONCLUSIONS

We have presented a study on the issues one would encounter in the design of an abort gap monitor for the Large Hadron Collider. We examined several options and believe that an instrument based on a gateable micro-channel plate photomultiplier is the most indicated for the task and can satisfy CERN specifications. We performed experiments with a Hamamatsu R5916U-50 tube both with beam (ALS and Tevatron) and on the bench. These experiments confirmed the favourable characteristics of the MCP-PMT and the relative effort required for designing an abort gap monitor around such a device.

REFERENCES

- [1] R. Schmidt, “Accidental Beam Losses and Protection in the LHC”, *Proc. ICFA-HB 2004*, (2004).
- [2] C. Fischer, “High Sensitivity Measurement of the Longitudinal Distribution of the LHC Beams”, *LHC-B-ES-0005*, (2003).
- [3] E. Shaposhnikova, S. Fartoukh and B. Jenneret, “LHC Abort Gap Filling by Proton Beam”, *Proc. EPAC 2004*, 211, (2004).
- [4] R. Witkove, P. Cameron, T. Shea, R. Connolly and M. Kesselman, “Beam Instrumentation for the Spallation Neutron Source Ring”, *Proc. PAC 1999*, 2250, (1999).
- [5] <http://www.bergoz.com>
- [6] M. Facchini, “Longitudinal Diagnostics Mirror Configuration for the LHC Beam”, *unpublished*, (2003).
- [7] <http://www.hamamatsu.com> for example.